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AUTHOR Duschl, Richard A.
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ABSTRACT

Interest in the application of the history and philosophy of science to science education raises important questions about the effect such considerations will have on educational practice. In this paper, the application emphasizes concepts related to theory testing and theory development specifically and to the growth of knowledge generally. This paper also presents the position that educators must consider carefully the application of tenets from psychology and epistemology if the application is to be effective. The need to avoid "final form science" is discussed, as well as theory testing, criteria for judging theories, theory change, and the growth of knowledge. A list of 52 references, a table of examples of theory change in science, a table of major scientific discoveries in the twentieth century, and models of the goal of science hierarchy and the triadic network of justification are included. (CW)

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A Framework for Applying History and Philosophy of Science to Science Education

Richard A. Duschl
Department of Curriculum & Teaching
Hunter College - CUNY
695 Park Ave.
New York, NY 10021

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Introduction

Interest in the application of the history and philosophy of science to science education raises important questions about the affect such considerations will have on educational practice. Duschl (1988), Hodson (1988; 1985), Linn (1987), Novak (1977), Russell (1980), among others, have each argued for including history and philosophy of science in the design of science curriculum. An important issue here is what affect would a position which seeks to join together historical, epistemological and psychological principles have on curriculum planning, implementation, and evaluation. It is the intent of this paper to focus on the application of epistemological concepts derived from the history and philosophy of science to the teaching of science. The application will focus on concepts related to theory testing and theory development specifically and to the growth of knowledge generally.

It is a purpose of this paper to also present the position that educators must consider carefully the application of tenets from pyschology and epistemology if the application is to be effective. For classroom teachers, the concern is with their decision making about the design, selection, and implementation of instructional tasks. How should teacher decision making be guided? What combination of the contribution of cognitive science and epistemological frameworks is best? And, should this combination fluctuate with respect to the specific domain of knowledge under consideration? For students, the concern is with the heuristics and strategies they employ or are taught to employ by teachers either in problem solving or in learning. Should these procedures be invariant across knowledge domains? What is the most appropriate combination of declarative and procedural knowledge? For researchers, the issue is the degree to which the two domains can facilitate understanding in the other field of study. Can terms from each field be generalized without encountering lexical difficulties? Can procedures of knowledge growth derived from philosophical analyses which establish a logic of knowledge development be used with pupils as heuristics for meaninglully learning science concepts?

Background

A distinction can be drawn between the processes of science which address the origin and evolution of scientific knowledge claims and the processes of science which are associated with the gathering of evidence and with establishing the validity and reliability of scientific knowledge claims. These two sets of processes represent the two faces of science. Designing a science curriculum to stress only one of these processes of science will necessarily only present a partial picture of science. We have learned from historians of science that it is a false

assumption to assume that the knowledge claims of science have equal importance or equal status among scientists. A challenge we face then is how to determine what knowledge is most important.

Contemporary teaching and learning models in science education - i.e., the learning cycle (Karplus, 1977; Champangne, 1988 [These two models have the same lable but are conceptually quite different]), the conceptual change or cognitive accomodation sequence (Nusbaum & Novick, 1982); and the generative learning model (Osborne & Wittrock, 1983), emphasize various psychological bases for learning science. Psychological principles are important but other factors need to be addressed in a comprehensive curriculum. Eisner (1985), for example, suggests that there are five basic orientations a curriculum can have. These are:

1. Curriculum as Technology
2. Personal Relevance
3. Development of Cognitive Processes
4. Social Adaptation and Social Reconstruction
5. Academic Rationalism.

Science education has emphasized to varying degrees orientations 1, 3, and 5 over the past 30 years. Orientation 1 focuses on strict systematized planning of meaningful goals assessed with behavioral objectives. It is safe to say that this orientation is the dominant orientation found in the majority of our schools. In this orientation, what to teach is not a decision to be made by the classroom teacher. Orientation 3 was the dominant focus of the 1960s elementary science curriculum projects sponsored by the National Science Foundation; i.e, Science-A Process Approach, SCIS, and ESS. Here through carefully designed instructional strategies the emphasis is on intellectual development and the cultivation of cognitive processes. In this orientation it is important to create a learning environment in which the student is an active agent in the process of learning.

Orientation 5 can be found in the secondary science curriculum projects sponsored by NSF. Here the focus is on informing students about the special patterns of thought which apply to a discipline. In the case of science, students learn what it means to think like a biologist, chemist, geologist, or physicist. This orientation is the preferred orientation of liberal education proponents. Very recently, orientations 2 and 4 have begun to assert an influence on science education programs. Orientation 2 can be found in the popular Science-Technology-Society approach (Bybee, 1987; Yager, 1988; Yager 1989) and orientation 4 is a part of the environmentally focused global education programs (Bybee, 1984).

It is my position (Duschl, 1986) that academic rationalism can subsume the other four orientations when epistemological frameworks which focuses on both faces of science are included. One key to this subsumption lies in the realization that science has the two faces we

identified above - a testing or justification face and a development or generation face. The second key is to recognize the central role theory development, replacement, and modification has in the growth of scientific knowledge.

Avoiding Final Form Science

Theory change is a natural element of all scientific disciplines. It is impossible in our classrooms, given the curriculums we are expected to teach, to avoid characterizing science as a dynamic evolving body of knowledge. The growth of scientific knowledge today is unparalled when compared to any other time in history. The infusion of science into our culture is gaining importance with each decade that passes. Consider the theory changes that have occured the last several centuries; see Figure 1. Next consider the discoveries made in science during this century; see Figure 2. The challenge we face is how to accurately capture the evolving, developing character of scientific knowledge while at the same time not loosing our appreciation for the rationality of science.

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One goal of precollege science education programs is to teach students about the tentative nature of scientific knowledge claims. Science, we stress, is a discipline which continually questions. Evidence that this goal has not been met, that students hold and develop a final form view of science has been documented in the science education research literature (Rubba, 1977; Welch, Klopfer, Aikenhead, & Robinson, 1981). The prevailing view among learners about the nature of science reflects an authoritarian view of science. Such a view maintains scientific knowledge is presented as absolute truth and as a final form.

The position taken in this paper is that scientific theories when properly represented can provide science educators with a powerful set of guidelines to format the planning and implementation of science instruction. Proper representation requires that both faces of science be addressed; the products of what we know as well as the processes of how we have come to know. To this end four frameworks are introduced. Ronald Giere's (1984) test of theories and Robert Root-Bernsteins (1984) four criteria for theory evaluation represent two frameworks for judging theories. Larry Laudan's (1984) Triadic Network for describing changes in cognitive values and Dudley Shapere's (1982) Tripartite division of the process of observation represent two frameworks for characterizing changes in scientific theories. Within each of these four frameworks, there are useful catagories and partitions that can guide the science teacher in their selection and sequence of science concepts.

Testing Theories

The approach here is a pragmatic one. Philosophically speaking, the discussions which follow are instrumental ones. In an attempt to provide a procedural format teachers and students can employ to assess scientific knowledge claims, liberties are taken in the selection of philosophic models and frameworks. I recognize fully that each of the models by itself is incomplete as a full and satisfying characterization of the growth of scientific knowledge. But, this does not dismiss the fact that such models provide pragmatic bases for guiding the teaching and learning of science. Furthermore, the argument is made that by adopting a curriculum perspective which evolves from a complex set of scientific processes based on epistemological principles - processes which seek to describe the testing of knowledge claims as well as the generation of knowledge claims - a broader set of curriculum orientations can be integrated in a K-12 science curriculum.

Testing Theories with Arguments

Being able to rank theories according to the status they hold among a community of scientists suggests that a set of criteria must exist that can be used to assess the

adequacy/truthfulness of a theory. Testing of scientific theories is difficult. It is simplified if we accept the ideas that there are levels of theories (Dulch, 1982; Radner & Radner, 1982) and a complex set of variables with which to evaluate theories.

One useful schema for testing theories is proposed by Ronald Giere (1984). First, he suggests, treat a scientific theory as a hypothesis, a hypothesis in which a theoretical model is making a claim about the real world. Let us call this claim a theoretical hypothesis. Next, treat this hypothesis as both a contingent statement - it can be either true or false - and a conclusion of an argument. An argument is a set of premises (P_1 P_2 . . . P_n) which lead to a statement of a conclusion. An argument is analysized in either one of two ways, 1) test the truthfulness of the premises, all premises must be true, or 2) test the internal consistency of the set of true premises, there can be no contradictions. Putting a theory into an argument form we can now test or justify the conclusion of the argument by examining the premises used to develop the argument. In other words, it is possible to format a test of the theory based on the pieces of information which make up the theory.

The basic elements for a test of a theoretical hypothesis are the hypothesis(H), the prediction (P), the initial conditions(IC), and the background knowledge(B). H is the theory being tested, P is the predicted occurrence of the possible state of some real system described by the theory, IC are the states of the system before considering this hypothesis - the known facts if you will, and B represents the existing knowledge claims of science that the hypothesis shouldn't refute , i.e., the center ideas of science.

Breaking a theory down to these constituent parts helps us to decide where the strengths and the weaknesses of the argument lie. As it concerns teacher planning, this strategy enables us to have a strategy for determining the most important content - that which informs us about our scientific theories.

Essentially, the strength of the argument is determined by the strength of the theoretical hypothesis to account for the prediction while not coming into conflict with either the initial conditions or the background knowledge. To challenge the prediction, the conclusion of the argument, we can attack any of the premises. We can attack H, we can attack the IC upon which the hypothesis is based, or we can attack the premises of B the hypothesis chooses to include. An example will help to clarify the argument strategy test of a theory.

An interesting episode in the history of science will serve as the basis of our example. At the beginning of the 20th century Alfred Wegener, a German meteorologist, put forth the theoretical hypothesis that the Earth's continents were once together as a single land mass and then drifted apart to the positions we find them in today. In 1926, geologists at the annual meeting of the American Association of Petroleum Geologists soundly rejected this idea of moving continents. So much so that for the next 30 years there was little attention paid to drifting

continents. In fact, those geologists who continued to profess allegiance to the idea of drifting continents jeopardized their professional standing in colleges and universities. In 1955, however, the idea of drifting continents was reintroduced and ultimately led to our present Theory of Plate Tectonics. It is one of the few instances in which a rejected theory was revived. Let's look at the arguments using Giere's schema for it helps us to understand how this change in theory occured.

H -
The continents on the surface of the Earth were once joined together as a single land mass.

IC -
1) The continents on the opposite shores of the Atlantic can be pieced together like a puzzle.

2) Glacial deposits and plant fossils of the same age are found on the continents of S. America, Africa, Australia, and Antartica.

3) There isn't enough water on the planet to make a glacier large enough to extend to these continents given their present positions; nor could the fossils which are found in the rocks transport themselves across the oceans.

4) Geological structures, i.e., faults and rock types, of the same age and with similar lithologies and orientations can be found on N. and S. America and on Africa.

B -
Physical theories hold that the earth is a solid object.

P -
The continents on the surface of the Earth are moving with respect to one another or drifting.

P is the conclusion of the argument which was rejected by the geologists in the 1920s. And it was rejected for rational reasons (Frankel, 1983) because the background knowledge B of geologists, that is to say the center theories they held about the structure of the Earth, did not provide for other than a Earth solid through and through. Subsequently, the prediction of drifting continents also refuted the laws of physics since there was no mechanisms to allow for solid rock to move through solid rock. The premises of the argument were not internally consistent.

Not until a change in B came about could the P of drifting continents be advanced. Such a change did eventually come about through the study of earthquake or seismic waves. The study of the behavior of seismic waves suggested that the earth was not entirely solid. In order to explain the patterns of data being collected by seismographs, a liquid core model of the Earth had to be adopted. Now that the veil of a solid core Earth had been lifted, seismologists also found it prudent to propose,that the upper section of the Mantle was more accuratply describe as a plastic

substance rather than as a solid. Shifting the B from a solid core earth to a liquid core earth was the critical turning point which enabled drift theory to be considered a viable explanation for the varying geomagnetic patterns found in rocks on the British Isles (Takeuchi, Uyeda, & Kanamori, 1970).

The usefulness of this test for science teachers resides in the way that it partitions broad theoretical statements into a set of smaller statements - theoretical hypothesis, background knowledge, initial conditions and a prediction. Once partitioned, teachers are now in a better position to invoke instructional strategies which lead to meaningful learning by students.

It is a fundamental maxim today of effective education practice that sound instruction seeks ways to partition knowledge claims into parts and then establishes the relationship among the parts. Novak and Gowin (1984) refer to this linking of knowledge claims as meaningful learning. Furthermore, they suggest that the basis of meaningful learning is for learners to develop a sense of the metaknowledge of the topic to be learned. Metaknowledge is the structure of the knowledge to be learned. Another way to describe metaknowledge is it is the syntax of the network of concepts to be learned.

With a familiarity of the metaknowledge, learners are better able to identify for themselves missing elements in the process of meaningful learning. Thus, Novak and Gowin (1984) relate metaknowledge with metalearning. Think of metaknowledge as knowing what to know and metalearning as learning how to learn. In the case of Giere's scheme for testing theories, metaknowledge would represent knowing the component of the argument; i.e., H, IC, B, P. Through the analysis of the parts it is possible to both introduce learners to the structure of the knowledge claim to be learned as well as to explore strategies for learning to use the structure as a tool for learning.

Thus, if the knowledge claim under investigation is a complex statement like a scientific theory, then effective instructional practice will first establish the parts or structure of the theory. The next step of instruction will establish the relationships which exist between or among the parts of the theory, and the final step will explore the degree to which the theory holds up against prevailing evidence, reason, and social conditions. These three steps when taken together help to establish the metaknowledge framework of the theory.

The three steps, as originally designed, are a part of the questioning strategy advocated in the Pattern of Inquiry Project (Connelley & Finegold, 1977) which follows a pattern of structural, functional, and evaluative questions. Structural questions are 'what' type questions that help students understand the parts of the inquiry. Functional questions are 'how'-type questions that enable students to understand how one part is related to another part. Evaluative questions are 'why'-type questions which seek to establish the degree of confidence we can have in the knowedge claims being proposed. In brief, this questioning triad seeks to establish the

degree of legitimate doubt we can associate with scientific knowledge claims.

Once subdivided, the theory is now capable of analyses which seek to establish the degree of legitimate doubt we can attach to the theory. The task for the teacher is to examine with students 1) the initial conditions the theory must account for or explain, and 2) the background knowledge with which the theory must be consistent. Just like the analysis of any other argument, the premises of an argument must be true - here the initial conditions and the background knowledge - and the relationships between the premises must lead logically, i.e., not contain contradictions, to the conclusion of the argument. A theory free of false premises and free of contradictions is a theory which will carry very little or no degrees of legitimate doubt. Central theories and frontier theories typically meet these criteria. On the other hand, a theory which contains false premises and/or contradictions among the premises is a theory which will have degrees of legitimate doubt attached to it.

The important point being made here is that a theory itself isn't replaced, abandoned, or rejected. Rather it is the parts of the theory that are replaced, abandoned, or rejected. In this way we can establish a rational line of argument for the changes which occur in science. It also is a procedure which requires we look at the parts, a strategy useful for planning and implementing instruction. Thus, let us explore further other mechanisms for partitioning theories and theory change processes into parts that can help us in formating instruction.

4 Criteria for Judging Theories

Robert Root-Bernstein (1984), as part of a collective response and critique to the rise in scientific creationism (Montagu, 1984), suggests that scientific theories can be judged by four fundamental criteria - logical criteria; empirical criteria, sociological criteria, and historical criteria. Root-Bernstein's framework extends Giere's logical empirical orientation and also includes two new sets of criteria that focus on external forces to theory change, namely sociological criteria, and on internal forces to theory change, historical criteria. Let us explore each of these four sets of criteria in more detail in order to acquire a sense of the component parts that can enter into our instructional decision making.

Logical Criteria - Theories can be judged by four primary logical criteria (Root-Bernstein, 1984; p 65):

1a - It must be a simple, unifying idea that postulates nothing unnecessary ("Occam's Razor");

1b - It must be logically consistent internally;

1c - It must be logically falsifiable (i.e., cases must exist in which the theory could be imagined to be invalid);

1d - It must be clearly limited by explicitly stated boundry conditions so that it is clear

whether or not any particular data are or are not relevant to the verification or falsification of the theory.

After carefully considering each of these four criteria it should become clear why they are essential to theory evaluation. "Theories must make clear patterns of things and relationships between things" (Root-Bernstein, 1984). There are obvious similarities between these four logicla criteria and those Giere proposes in his argument scheme for testing theories. Properly construed a theory will be succinct and straight forward in the explanation it seeks to provide. The theory will not contain statements which contradict other statements in the theory. The theory must be testable both in terms of justifying the theory and in terms of refuting the theory - Giere's (1984) two conditions for a good test.

Good theories provide sound explanations and sound explanations are based on logically sound arguments. The requirement that a theory be precise in delineating the phenomena it seeks to explain establishes both the domains in which it applies and the domains in which it fails to be relevant. Unbounded theories can not be falsified and therefore cannot be shown to have any weaknesses. The ability of scientists' to identify explanatory weaknesses and logical inconsistencies are basic elements to the self-correcting nature of the growth of scientific knowledge; "(S)elf-correctability is precisely the characteristic that gives scientific theories their epistemological power: a theory that is incorrect or incomplete can, by attempts to falsify it, reveal its faults or limitations and so be corrected or extended." (Root Bernstein, 1984; p 66).

Empirical Criteria - Empirical criteria are critical elements to the development of a data foundation to the growth of scientific knowledge. Recall that the Goal of Science Heirarchy began with the analysis of data. The empirical criteria of theory evaluation focus on describing what counts as observable measurable data that can be used to verify tests of theories. The four criteria state (Root-Berstein, 1984; p 66):

2a - A theory must be empirically testable itself or lead to predictions or retrodictions that are testable;

2b - A theory must actually make *verified* predictions and or retrodictions;

2c - A theory must concern reproducible results;

2d - A theory must provide criteria for the interpretation of data as facts, artifacts, anomalies, or as irrelevant.

These four criteria enable us to understand one mechanism for change in scientific knowledge. Criteria a,b and c are straightforward and do not require further elaboration. But criterion d is central to the growth of scientific knowledge and a powerful tool to be used by teachers in the planning of science instruction that avoids final form accounts.

In criterion d we see once again that all things in science are not equal. Some data count or

are relevant, some data are not. I want to turn our attention to the data that are not initially construed to be relevant. As new technologies emerge (i.e., magnetic compass, microscope, vacuum chambers, cathode ray tubes, electric gerferators, clocks) new modes of observing and measuring are developed which, in turn, generate new sets of empirical data. This new data born of new technology typically falls outside of the established explanatory boundries of known theories but are nonetheless too valid to dismiss.

Such data or empirical facts are referred to as anomalous data and are an important force in changing the explanations of science. When the amount of anomalous data becomes large enough to prompt some scientists to call into question the existing central explanations/theories of science, Thomas Kuhn (1962/1970) suggests science enters a period of revolution, a revolution whose purpose is to seek a conceptual change in what data count as fact, antifact, anomalies, or as irrelevant.

The identification of anomalous data by teachers in the course of science instruction provides students with a tangible link to the mechanisms of change in scientific knowledge. And, as pointed out such data are all too frequently linked to advances in technology. Thus, an important aspect of science education is outlining how the processes of observation and measurement have been changed over the centuries to rely less and less on the direct role of our human senses. We will explore this important process of change in the last section of this paper.

Today, however, magnetic probes describe the workings of the human body and the characteristics of the Earth's mantle. Satellites are used to view the surfaces of planets employing spectra of electromagnetic radiation invisible to the naked eye. Statistical procedures enable investigators to make predictions and retrodictions on subcomponent parts of populations. In each of these examples, the collection and manipulation of the data need not involve the active use of our senses. Computers, state of the art electronics, and our theories of the physical universe have made it possible to redefine what it means for something to be empirically testable, verifiable, and reproducible. In turn, these changes have altered how we treat data.

Sociological Criteria - Science does not function in isolation. And, similarly, scientists do not practice their trade or conduct their inquiries without influence from the outside. The influence here is directed toward the collective contributions scientists make to each other in the pursuit of answers to scientific problems. When private knowledge becomes public knowledge there is a ripple sent across the scientific landscape. Today the forum for the transmission of private knowledge into public knowledge is through journal manuscripts and conference proceedings. In 19th century England, the prevalent forum were the meetings of the Royal Society of London. Here gentlemen would gather to watch demonstrations and debate the

implications of experiments conducted by Robert Boyle and his assistant Robert Hooke or to hear the result of the global explorations of Charles Darwin or Charles Lyell. Earlier still, learned monks and priests would meet to reconcile the implications of Aristotle's views of the universe with those of the church.

The communication of knowledge establishes standards and makes a record of what is to count as legitimate knowledge claims, as relevant problems for investigations, and as appropriate methods for conducting an investigation. Consequently, practicing scientists must accept the burden of responsibility to insure that their explanations have been checked against past as well as existing explanations. It is in this spirit of knowing what else exists that Root-Bernstein offers his four sociological criteria for determining the validity of a theory (p 67). A theory must:

3a - resolve recognized problems, paradoxes, and/or anomalies irresolvable on the basis of preexisting scientific theories;

3b - pose a new set of scientific problems upon which scientists may work;

3c - posit a "paradigm" or problem-solving model by which these new problems may be expected to be resolved;

3d - provide definitions of concepts or operations beneficial to the problem-solving abilities of other scientists.

A scientific theory which ignores the past is always held suspect. Of course there is often very differenct opinions about what problems are most worthy of investigation. The history of science is fraught with many examples of periods of consensus of opinions and dissensus of opinions about the theories, methods, and aims of science. Pointing out examples of these to students is a valuable element of a sound science education. A fuller discussion of this application of philosophy of science follows the discussion of the last of Root Bernstein's criteria.

Historical Criteria - The last of the four theory evaluating sets of criteria proposed by Robert Root Bernstein is historical criteria. Historical criteria insure that indeed the growth of scientific knowledge has followed a path which clearly establishes correctability. The three historical criteria state that a theory must (p 67-68):

4a - meet or surpass all of the criteria set by its predecessors or demonstrate that any abandoned criteria are artifactual;

4b - be able to accrue the epistemological status acquired by previous theories through their history of testing - or, put another way, be able to explain *all* of the data gathered under previous relevant theories in terms either of facts or artifact (no anomalies allowed);

4c - be consistent with all preexisting ancillary theories that already have established scientific validity.

The knowledge claims of science do not occur within a vacuum. The activities of science and therefore the knowledge claims of science must have meaning within a cognitive and methodological framework of those scientists who are part of the at-large scientific community. Thus, we speak of scientists functioning with research programmes (Lakatos, 1970) or research traditions (Laudan, 1977) and of ideas belonging to certain worldviews or paradigms (Kuhn, 1962/1970). Of course, the unifying central theory elements of science can change also but such revolutionary changes in scientific knowledge are a less common occurance than the frequent steady cumulative type of change that occurs within a research programme or research tradition. The next philosophical frameworks we shall examine focuses on an analysis of what is involved when one central theory of science is replaced by another.

Theory Change and the Growth of Knowledge in Science

Historical studies of the growth of scientific knowledge (See Brush, 1988 for a useful bibliography on the history of modern science) have had the effect of altering philosophers' views of what characterizes knowledge growth in science. Prior to the influx of history of science during the 1950s and 1960s, the growth of scientific knowledge was modeled after physical science theories. Befitting of the sciences which fit quite nicely with mathematical formulations, the physical science models promote an accretionary mechanism to describe the growth of knowledge. In the accretionary mechanism new knowledge is added to old like layers of aluminum foil to an aluminum foil ball.

But scholary writings in the history of science and the sociology of science have altered this accretionary view to one which argues for the replacement and subsitution of knowledge claims. Put in terms of our aluminum foil analogy and employing the theory evaluating criteria of Root-Bernstein, anomalous data born from new techniques and technologies for collecting data require that we sometimes need to start new balls of aluminum. Thus, contemporary principles of the structure of knowledge speak to the importance of establishing a basis for accepting scientific theories as both revisionary and tentative (Van Frassen, 1980; Suppe, 1977). An adequate philosophy of science, therefore, must understand both how theories are generated and how theories are revised, altered, or replaced.

It is this very idea of revision and replacement in scientific theories that has prompted educational researchers (Posner, Strike, Hewson, & Gertzog, 1981) and psychologists (Carey, 1986) to suggest that principles of theory change can be applied to how children learn science. It is also important to recognize that the application of conceptual change to education is adopted

from philosophers of science ideas about the revisionary charactersitics of the growth of knowledge.

In this section, we turn our attention to frameworks which assist us in describing this mechanism of conceptual change. Our task is to take from epistemology and apply it to the task of teaching science. The fact that the cognitve processes children employ when learning science happen to have much in common with the epistemological frameworks of science theory development serves as a partial justification for applying epistemological frameworks to teacher decision making. The principal focus of our discussion will be two models which describe the processes of theory change:

1) Laudan's (1984) Triadic Network.

2) Shapere's (1982) Tripartite Process of Observation.

Mechanisms of Change

Arguments that the structure of scientific theories and the structure of learners' cognitive frameworks/schema have much in common must consider both the structural characteristics and the developmental characteristics of these conceptual frameworks. Structurally, scientific theories and cognitive schema seem to have much in common. Theories can be thought of as a network of facts, principles, and lawlike statements which are joined together by accepted methodological practices and by common goals or aims of inquiry. Cognitive schema from this structural perspective are conceived as clusters of concepts and propositional statements which are governed by rules of logic and by social values that together guide the synthesis of our knowledge.

A problem occurs though when it is necessary to describe the mechanisms for change in the structure of theories or in the structure of conceptual schema. There has traditionally been among philosophers a clearer sense of what constitutes a logic of justification than what characterizes a logic of generation. With the recent application of history of science and the emergence of fully developed center theories in biology and geology philosphers of science have been in a better position to develop guidelines that describe the generation or development of theories.

But we in education have yet to witness a conversion in our curriculum to these new views of science. A negative outcome of the clearer sense of models describing a logic of justifying scientific knowledge has been an exclusion of the dynamics and mechanisms of change in scientific knowledge. In short, the important roles of theory refinement, adjustment, and subsitution are excluded in science classes. Included are factors which promote a final form representation, or should we say misrepresentation, of science.

What I want to challenge is the more typical hierarchical straight path growth to a final

form view of science. Thus, I am here renouncing the goal of science heirarchy - see Figure 3 - as an adequate model for explaining how change occurs in scientific understanding. For heirarchical models, like other building block approaches or accretionary models (e.g. the aluminum foil ball analogy) of the growth of scientific knowledge, underestimate how important the mechanisms of change to methods and aims are in the growth of scientific knowledge. Simply stated, for now, such models unduly emphasize the knowledge successes of science and the final form of scientific knowledge. I do not wish to challenge the position that science has not provided increasingly more accurate accounts of the structure of nature. It has. It is difficult to deny the fact that over the past three centuries our scientific understanding of nature has improved.

What I do want to challenge is the one-sided approach which emphasizes the consensus building mechanisms of change. Yes, the general trend has been one of success but historians of science have found that this long-term positive trend has many instances of retrograde motion, stasis, and dead-end lines of inquiry. The character of theory building is more accurately described as an activity involving replacement and substitution than it is an activity involving accretion and addition. The conclusions drawn by historians of science suggest the growth of scientific knowledge progresses through periods of consensus and dissensus of opinion among its practitioners. Furthermore, when changes to theories do occur these changes are not global holistic changes but rather are more accurately described as piecemeal in character. Again, we see a partitioning of the process and thus yet another opportunity exists for us to base teacher decision making on the parts of an epistemological framework.

When changes in science are described in broad details - once we believed the Earth was at the center of the universe but now we believe the Earth revolves around the Sun- we are too often left with the impression that changes in scientific knowledge come about quickly and holistically to a community of scientists. We mentioned earlier that Kuhn (1962/1970) refered to the periods of change in which new center theories come to replace old center theories as scientific revolutions. He partitions the activities of a scientific community into two parts; periods of normal science when there is consensus of opinion about the center theories of a scientific discipline and periods of revolutionary science when there is dissensus of opinion about the center theories of a discipline. It is through periods of revolutionary science that change and progress comes to scientific knowledge.

The problem here is that hierarchical models of conceptual change (e.g. Posner, Strike, Hewson, & Gertzog, 1982) assume that with changes in knowledge central commitments - here to mean commitments to scientific theory - there are concommitant wholesale changes to all other elements of scientific activity, specifically commitments to investigative methods and aims. Such oversimplifications of the process of change in science eliminates from consideration

the essential and important roles changes to methods and aims play in the process of change. In turn, it also underestimates the degree to which replacement and substituion are factors in the growth process of scientific knowledge. One effective way to combat final form versions of science in our classroom is to carefully examine the process of theory change through an analysis of changes to knowledge, methods, and aims.

The models of theory change which follow once again, as with the models of theory evaluation before, provide a basis for delineating the parts of the process. With a knowledge of the parts, science teachers have yet another set of guidelines for informing them in their planning and in their implementation of science lessons and science units.

Triadic Network

Hierarchical models of holistic conceptual change put too much emphasis on the affect changes in theoretical commitments have on changing methodological commitments and investigative aim commitments of scientists. Such a view of change to scientific theory is faulty for several reasons according to Laudan (1984). First, holistic change models inaccurately describe how scientific consensus and dissensus take pl, .e. Laudan argues with convincing evidence from history of science that change in science is less holistic and more piecemeal is character. For Laudan, the notion of change is one in which changes to scientific theories, methods, and aims can and do occur separately within distinct and mutually exclusive periods of time. Thus, although there is a change is theory commitment there need be no instantaneous change in commitments to methods or aims.

The second fault Laudan finds with holistic models of scientific change is the emphasis placed on the role of consensus activities in science. On those occasions when enough anomalous data has accumulated to provide evidence that a change in science is needed, these are times when dissensus activities among scientists dominate. Hierarchical models of change that promote final form versions of scientific knowledge tend to smooth over this important replacement and substitution component of scientific change. It is important not only because it more accurately decribes the process of change in science but also because studies in cognitive science clearly demonstrate that in learners new explanations are not adopted nor even considered until old explanations are shown to be inadequate. Thus, what we know about the dynamics of scientific change we can apply to the classroom. We will explore specific strategies in the next chapter.

A third problem Laudan finds with holistic models is they frequently overlook the important role aims and methodology have in establishing the anomalous evidence which brings about conceptual change. This point is demonstrated by the two modes of theory change described by the 'Goal of Science Hierarchy' - see Figure 3. One type of change involves the development of a new center theory which then causes us to interpret exising data in a new light. Such a change

is representative of holistic models where a change in theoretical commitment changes how we see, interpret and represent data. The second model of center theory change is when new aims and methods of science give rise to new vistas of inquiry and thus new sets of data. Here is where we might invoke Root-Bernstein's 'Empirical Criteria' as a learning strategy. When the new data fit into the anomalous category as opposed to either the factual, artifactual, or irrelevant categories then change is imminent and necessary.

Insert Figure 3 About Here

We must ask, therefore, what activities in science spawn anomalous data. Certainly one dominant source of new data is the adoption of new technological devices by scientists. These new devices affect the methods scientists employ. Consider once again the impact the microscope, telescope, seismograph, x-ray tube, or computer, we could go on and on here, have had on the form of data scientists have at their disposal. Laudan's piecemeal approach focuses our attention on the important role the tools, strategies and technologies of scientific method have in bringing about dissensus activities and, thus, eventuating change in science.

In a similar vein, changes with the aims of scientific inquiry can also provide the impetus needed for spawning new sets of anomalous data. The investigative methods of science determine how we look. The investigative aims of science determine where we look. Consequently, when considering influences on aims we must recognize the important role social factors have on the activities of scientists and scientific institutions. World War II, as we have already discussed at the beginning of the book, had an enormous affect on the rate at which new technologies were developed. Our space program is an example of how a scientific institution with political and financial support can produce theory-altering sets of data. Clearly, our knowledge of the planet Earth today, a knowledge forged from data collected by various satellites, is significantly different than the knowledge of the Earth we had prior to 1960. One significant example is hurricane tracking and warning.

What is being suggested is that the process of knowledge growth is not governed solely or dominated by commitments to theories. There are according to Laudan (1984) three levels of commitment for scientists:

1) theoretical commitments,
2) methodological commitments, and,
3) goal of science or aim commitments.

In constrast to hierarchical models which emphasize theory commitments over the other two, none of the three levels in Laudan's model - theory, method, aim - has a privileged status over the other two levels. Rather Laudan (1984) argues " there is a complex process of mutual

adjustment and mutual justification going on among all three levels of scientific commitment. . . . The pecking order implicit in the hierarchical approach must give way to a kind of leveling principle that emphasizes the patterns of mutual dependence between these various levels" (p 62). Thus, Laudan proposes that knowledge justification in science involves a developmental component which can be represented as a Triadic Network (See Figure 4) were:

1) Aims (**A**) justify Methodology (**M**) and must harmonize with Theories (**T**);
2) **M** justifies **T** and exhibits realizability to **A**;
3) **T** constrains **M** and harmonizes with **A**.

Insert Figure 4 About Here

Whereas hierarchical models (Kuhn, 1962; Lakatos, 1970; Laudan, 1977) argue for wholesale or holistic changes in **M** and **A** whenever changes in **T** occur, the Triadic Network suggests that changes to scientific knowledge are more piecemeal in character. Hence, the piecemeal notion of change is one in which changes to **T**, **M**, and **A** can and do occur separately and within distinct and mutually exclusive periods of time.

According to the Triadic Network model of change it is possible for scientists working in a discipline to alter theoretical commitments but still maintain existing methodological and cognitive aim commitments developed from a previous theoretical framework. For example, the theory of evolution has had little , if any, affect on the methods of taxonomic classification (De Queiroz, 1988). Whereas Darwinian evolutionary theory focuses on the common ancestry ordering of organisms, established methods of "(c)lassification consists of ordering entities into classes, groups defined by the attributes of their members" (De Queiroz, 1988; p 238). The advent of evolutionary theory does little to change the attributes of what makes a reptile a reptile or a bird a bird. But it does change how we think of the grouping of organisms, taxonomies based on the natural process of descent and thus its product common ancestry would provide a different way of grouping living things.

The problem with emphasizing commitments to T and then T_1, T_2, etc. without any discussion of **M**, **A** or timeframes is it reinforces final form science. Presenting the growth of scientific knowledge as series of theory shifts risks representing the growth of scientific knowledge as a series of whimsical irrational shifts among scientists. Left aside are the timeframes and the details of the perfectly reasonable and rational events which contributed to the changes in beliefs.

The point, of course, is that a sequence of belief changes which, described at the microlevel, appears to be a perfectly reasonable and rational sequence of events

may appear, when represented in broad brushstrokes that drastically compress the temporal dimension, as a fundamental and unintellegible change of world view. (Laudan, 1984; p 78).

We in science education are often guilty of presenting the growth of scientific knowledge in a holistic framework. Our curriculums typically paint pictures of change with broad brush strokes which totally mask the timeframe and the critical events that bring about changes in both what we know and how we have come to know it. In recommending the application of the Triadic Network to teacher decision making, I am suggesting that a similar "leveling principle" be integrated into our science teaching and lesson planning. This epistemological framework reminds us of the need to include the equally important changes to methods and aims. Again by looking at the parts, we are better informed about how to:

1) meaningfully present science to novice learners, and;

2) provide learners with strategies for constructing their knowledge of science.

Thus, Laudan's Triadic Network might look like this when applied to the planning and implementation of science units:

T - Theory lessons would emphasize the background knowledge (BK) and initial conditions (IC), Giere's terms, of the unit. Here student's would need to be provided instruction and learning strategies on how to meaningfully link scientific concepts. The emphasis on concepts recognizes that there is a core content to science . Effective science instruction is stymied, however, if students attach different meanings to the core concepts of the content. Establishing consensus of opinion to core concepts among class members is what conceptual change teaching is all about. If students' understanding of a concept represents a dissensus of opinion among the class, then the teacher needs to implement concensus forming instructional strategies; e.g., Giere's and Root-Berstein's frameworks of theory evaluation. Similarly, if students have a consensus of opinion about the meaning of a concept of set of concepts but the meaning is incorrect, then the teacher needs to invoke a dissensus forming instructional strategies focusing on the development of anomalous evidence; i.e., discrepant events.

M - Methods lessons would focus on the acquistion of evidence. A very critical element in establishing anomalous evidence is the changes to our beliefs about what counts as observational evidence. We will explore the issue of observation and evidence in more detail shortly through Shapere's Tripartite Observation scheme. But here let us again be mindful of the rapid technological advances taking place this century and how these new tools of inquiry have provided us with new ways of seeing. To expect learners to accept at face value the credibility of scientific data without any clues concerning the process/tools of data collection, data manipulation, and data interpretation is wrong. Such an expectation once again reinforces final form science and

presents science as a series of success stories. Left out are the various false starts, dead-end lines of inquiry, adjustments, and misdirections often made by scientists. **M** lessons would impart to students an understanding of how scientists have learned how to learn. In one sense, science is an activity of answering questions which give rise to new questions. How we choose to seek solutions to known questions and to identify new questions is a critical element of the growth of scientific knowledge.

A - Aims lessons would focus on what scientists' and society believe to be important cognitive goals of science. In other words, these lessons would outline for students what is or was considered most worth knowing. At any given point in time, there are a set of standards which guide scientists in the selection of important research problems, in the design of methods to solve the problems, and in the establishment of criteria for deciding what counts as a good experiment and, therefore, what constitutes good data or bad data in solving the problem. The formation of standards is a critical element in a proper representation of the growth of scientific knowledge. We have already outlined Root-Bernstein's four criteria but there are internal criteria to the activities of scientists. There are other important criteria which influence the scientific enterprise and these criteria fall under the heading Science-Technology-Society.

The activities of science do not take place in a vacuum. Social pressures do affect the formulation of standards scientific communities apply to research efforts and research funding. Present day examples of socially relevant scientific problems include global warming of the atmosphere, AIDS, secondary and tertiary recovery of oil reserves, solid-waste disposal, and superconductivity. Historical examples include the development of vaccines for polio, the construction of accurate calendars based on planetary motions, solving the genetic variability of crops, and succeeding at the separation of matter into elements.

Through an examination of the aims of science we see that there is an applied aspect and a basic aspect of science. We also discover that activities in the arenas of applied science and basic science are equally important to the growth of scientific knowledge. Similarly, then, so too is the teaching of how applied science contributes to basic science and vice versa. One of the best places to teach students about the interaction of applied and basic science is through examples of how we have learned how to learn about nature. The next section turns to the critically important role observation has in teaching us about nature and about how we have learned how to learn about nature. More exactly, we will outline yet another framework for guiding instruction about the interaction theories have with observations.

Theory & Observation

In this last section, I want to turn our attention to the rational development of changes in scientific observation and, therefore, to changes in what counts as observational evidence. Up to

this point we have focused on strategies to evaluate and represent theories. One other important aspect of understanding the role of theories in science is to examine the influence theories have on the process of scientific observation. Scientific theories represent our best reasoned beliefs about nature and natural phenomenon. As scientists have learned how to learn about nature, scientific theories have played an ever larger role in the definition of what constitutes an observation. Increasingly, scientific observations have come to deemphasize the role of the human senses in data collection in favor of instruments and methods based on the fundamental theories of science. The consequence of this shift for our students, is that it is becoming increasingly more difficult to explain how we know what we know.

We have learned that what we see is affected by what we know. Thus, although it is possible for two individuals to look at the same source of information it is nonetheless quite conceivable for them to 'see' two very different things. The issue here is the individual's perception of what they see. Hanson(1958) helps us understand this dilemma by distinguishing between two types of seeing; "seeing as" and "seeing that". Seeing as is an observation which is carried out without the benefit of prior knowledge. Here observations will focus on the literal description of patterns - a # is seen as two sets of parallel crossing lines. Seeing that observations, on the other hand, occur with the benefit of prior knowledge - a # is seen as the symbol for number. Thus, 'seeing that' observations have a specific meaning attached to them. When individuals have different knowledge backgrounds, then it becomes possible for them to look at the same phenomenon and yet see two different things.

A large measure of what we seek to accomplish in the science classroom is moving students from novice 'seeing as' observers or naive 'seeing that' observers to informed 'seeing that' observers. This is essentially what conceptual change teaching is all about. Patterns of earthquakes epicenters on a world map, direct numerical relationships between an accelerated mass and force, and the geographical range of organisms each imply specific meanings when understood in terms of prevailing scientific theories. For example, the observational fact that earthquakes occur has been known since the dawn of civilization. Explanations for why earthquakes occur, however, have been numerous and over the last 100 years alone include shifts in barometric pressure, gravitational effects of the moon and sun, isotatic rebound of mountains, plate tectonics, and rising methane gas (Duschl, 1987).

Any attempt to describe the adjustments and refinements that occur in science must provide a schema that outlines changes to the fundamental process of observation. Out of observation emerges the data and evidence that might represent anomalies to what is known. Shapere's tripartite portrayal of observation enables us to once again partition the role of theories in science and have another framework teachers can employ for making decisions concerning the planning and implementation of science lessons and students can employ as a

learning strategy for constructing a knowledge of science.

The ideas expressed here are taken from the collective writings of Shapere (1984). Shapere's philosophy of science argues that not only are there changes to the knowledge claims of science but there are also changes to our meanings of investigative processes and characterizations of science; i.e., what we mean by observation, laws, evidence, etc. Thus, he further suggests that standards scientific communities employ are also subject to change. In fact, there is little he would say doesn't change including meanings of words. But it is possible to trace the change and then to outline a process he calls the rational feedback mechanism to changes in science. This path is represented schematically in the Goal of Science Hierarchy (Figure 3) as the adjusting path emerging from the theory level.

In this tradition, Shapere (1982) takes the position that what has come to represent an observational event in science has also undergone a change. Specifically, it is a change where sense-perception evidence has come to take a back seat to theory-laden evidence. Put another way, what seeing meant to scientists in the 1800s is very different to what seeing means to scientists today. The distinction is two very different notions of 'seeing that'.

Before sketching an example of how theories effect observation - an analysis of how we see shifts in the rotation of the Earth - let us first examine Shapere's tripartite portrayal of scientific observations. By conceiving of the act of seeing as scientists themselves define seeing and not as philosophers of science define seeing, Shapere (1982) finds it prudent to represent an observation as a three part process:

1) the release of information by a source
2) the process of transmitting the information
3) the reception of information.

Thus, when we think of seeing as a biological process, visible bands of light from the sun reflect off object surfaces. These reflected waves of light travel through our eyes and project an inverted image of the object on the retina of our eyes. If we recognize the pattern of the image, that is we have a name or label of it, then our receptor - the brain - will be able to act on the information in the appropriate way.

The major premise of Shapere's position is that a data gathering process which is totally void of sense-perception activities (i.e., none of the human senses are involved in the acquistion of data) can still be counted as an observation if certain factors are taken into consideration. First, something is directly observable if information is received by an appropriate receptor and the information is transmitted without interference to the receptor from the source of the information, namely the object being observed. Second, observation is composed of the three steps listed above. This tripartite division of observation is significant because within each of the three component observation processes - source, transmission, receptor - scientists have

built up theories which relate directly to each phase. Thus, in our scientific knowledge there are:

- Theories of the Source;
- Theories of Transmission;
- Theories of Reception.

When we consider how this tripartite model applies to any single observational episode in science, e.g., seeing the core of the sun, observing the movement of crustal plates, seeing the structure of recombinant DNA, it is clear that the nature of the evidence which supports our best reasoned beliefs - our theories - are a product of the cognitive knowledge, the methods, and the aims of our investigations. We have learned how to learn about nature.

Consider how scientists are using distant quasars and satellite lasers to observe variation in the rotation of the Earth (Carter et al; 1984). The quasars and the satellites both emmit electromagnetic waves and represent the source of information. With respect to the use of quasars, an important piece of background knowledge about the source of the information (*Theory of the Source*) is that our present knowledge of the universe treats these distant stars as fixed points relative to the motion of the Earth. Therefore, it is possible to determine the distance to the point and treat it as a marker. *Theory-of-transmission* information propose that electromagnetic radiation can travel uninterrumpted from these distant sources to the Earth. Our confidence in this *Theory of the Transmission* information is supported by the transmission of millions of lines of communication signals in our atmosphere - ever try explaining to a child why the radio signals do not all play at the same time.

The background knowledge (*Theory of the Receptor*) of the approapriate receptor for information transmitted by distant quasars is quite diverse and indicative of how far and to what extent scientific reasoning and technology have become a part of scientific observation. The receptor of the information is a global network of radio telescopes linked to sophisticated computers. The entire technique is called **Very Long Baseline Interferometry** or **VLBI** for short. Reliability and validity of the instrumentation and of the theories involved is firmly established among the scientific community:

> The improved series of earth-rotation measurements presented here represent some of the early results of a concerted international effort to apply advanced technology to the study of geodynamics. In September 1983 Project MERIT (monitor earth rotation and intercompare techniques of observation and analysis). . .launched a 14-month observing campaign to study the earth's rotation. The VLBI, SLR (satellite laser ranging), and LLR (lunar laser ranging) observations collected under Project Merit are expected to yield the most detailed and accurate records of variations in the earth's rotation ever compiled. . . . The improved

> observational capabilities may well allow questions that have dominated the study of geodynamics for more than a century to be answered within the next decade. (Carter et al; 1984 p. 961, emphasis mine)

Advances in physical knowledge, in mathematical procedures, in computer science, and in scientific instrumentation have generated a rational feedback mechanism which has changed our concept of observation, "Thus, we say that what we have learned about the way things are has led to an extension, through a natural generalization, of what it is to make an observation" (Shapere, 1984; p 345). Essentially, we have learned how to learn and there is a developmental character to this process.

Concluding Statements

The theories scientists employ are an integral part of understanding what counts as an observation and what counts as evidence. When science education programs focus on final form science they avoid articulating the important theories of source, theories of transmission, and theories of receptors that contributed to the development of that final form knowledge. An examination and articulation of source, transmission, and receptor theories help students to understand the rational evolution of scientific criteria and in turn to better appreciate how scientists have come to think the way they do and to use the methods they employ. It also provides them strategies they can use to learn science.

The knowledge claims and investigative methods of science are quite remote to the average citizen. W and Z particles viewed by supercolliders, black holes seen by radio telescopes, million year old rocks measured by potassium/argon dating methods, models of biological and biochemical evolution derived from statistical probabilities, gene splicing with enzymes acting as biological scissors are examples of the claims and methods of science that make up our contemporary understanding of nature. This is strange wild stuff when only the final form of the knowledge is presented without any information about how we have come to arrive at this knowledge.

Through an examination of the development of scientific theories and scientific explanations, students can learn how scientists have not only acquired knowledge about nature but have also learned how to observe nature. Modern scientific knowledge and technology are meaningless when treated in isolation; teachers *must* include the background addressing how science arrived at a particular knowledge claim. Through an examination of the rational evolution of scientific accomplishments, an analysis of the development of knowledge and of the methods and criteria for seeking and acquiring the knowledge can take place. Such information is important to science teachers.

Research by Tobin and Gallagher , 1987) reveals that teachers are implementing instructional designs which do not take into consideration the full range of available knowledge needed to teach science meaningfully. Shulman (1986) describes this range of knowledge as knowledge of content, knowledge of pedagogy, and knowledge of curriculum and notes that:

> Teachers must not only be capable of defining for students the accepted truths of a domain. they must also be able to explain why a particular proposition is deemed warranted, why it is work knowing, and how it relates to other prosositions, both with the discipline and without, both in theory and in practice. (p. 9)

The results of a study on teacher decision making in science (Duschl & Wright, to be published)suggest that teachers give little, if any, consideration to the nature of the discipline from which instructional tasks are ultimately taken. This conclusion is consistent with the results of a study (Milman, Mergendoller, Marchman, & Packer, 1987) conducted with 11 seventh-grade life science teachers. The instruction of teachers was observed to determine the extent to which they made linkages between science content and its societal, reasoning, historical, or attitudinal implications. One result of this study was "teachers rarely or never addressed the noncontent components of science in their presentations and academic work assignments" (Milman, et al, 1987; p 611). Consequently, Milman et al conclude, and I concur, that there is a large gap between scientific literacy as a goal of science instruction and current teaching practice.

Based on the findings from Duschl and Wright (to be published), however, it is apparent that teachers' considerations for the nature of subject matter or discipline they teach, and for the structure of scientific theories within that discipline, could be helpful in determining what is the most important content or what is a preferred sequence of instruction to teach. If teachers were to select and sequence instruction units to mirror the development of scientific theories, then select reasoning skills and critical thinking skills implicit in this development would be included also. For a more extensive discussion of the application of history and philosophy of science to science education interested readers are directed to Duschl (to be published).

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Discipline	Century	Theoretical Core
Geology	18th	Neptunism - rocks formed by water
Geology	19th	Plutonism-rocks formed by fire and water
Chemistry	18th	Phlogistron explains burning; molecules (H_2O) are pure substances which have properties (spirit) of animate objects
Chemistry	19th	Oxygen explains burning; elements (H,O) are pure substances which have properties of periodicity
Physics	17th	Planetary motion is circular and at constant velocity; weight and mass are combined;
Physics	18th	Planetary motion is elliptical with changing velocity; weight and mass are separate;
Biology	18th	Life classified/grouped according to habitats; i.e. things that swim, fly, etc. Diversity of life explained by spiritual laws
Biology	19th/20th	Classication by morphology; diversity of life explained by mechanistic laws

Figure 1 - Examples of theory change in science.

1900-1919

Leo Baekeland discovers resin used to make nylons and plastics.
Alfred Binet develops IQ test which defines intelligence for 70 years.
Albert Einstein formulates relativity, helps create quantum theory, and establishes the reality of the atom.
Karl Landsteiner discovers blood groups enabling successful blood tranfusions.
Karl Pearson introduces statistics to the world of scientific decision making.
Lee de Forest invents vacuum tube and opens airwaves to radio and TV.
George Shull develops hybrid corn from crossbreeding experiments making it possible to feed the world.

1920-1939

Medicine is transformed from an art into a powerfully effective applied science with the discovery of antibiotics.
Raymond Dart shows Africa brought forth the first human species.
Nuclear Fission is discovered in radioactive materials.
Edwin Hubble deduces the Big Bang Theory from data of an expanding universe.
DDT inspires both agriculture and the environmental movement.
Vladimir Zworykin invents the television camera solving the problem of converting light to electricity and electricity to light.

1940-1959

Russel Marker synthesizes hormone used in birth control pills from Mexican yams.
Computers were initially developed to break Nazi codes but soon open up new worlds of data representation and analysis.
Chlorpormazine and **lithium** empty mental hospitals and change our understanding of mental illness.
Bell Laboratories invents the transistor and introduces solid state electronics.
Watson and **Crick** unravel the secret of DNA and alter our views of life.
Laser light discovery opens up new windows.

Figure 2 -Major twentieth century discoveries in science.

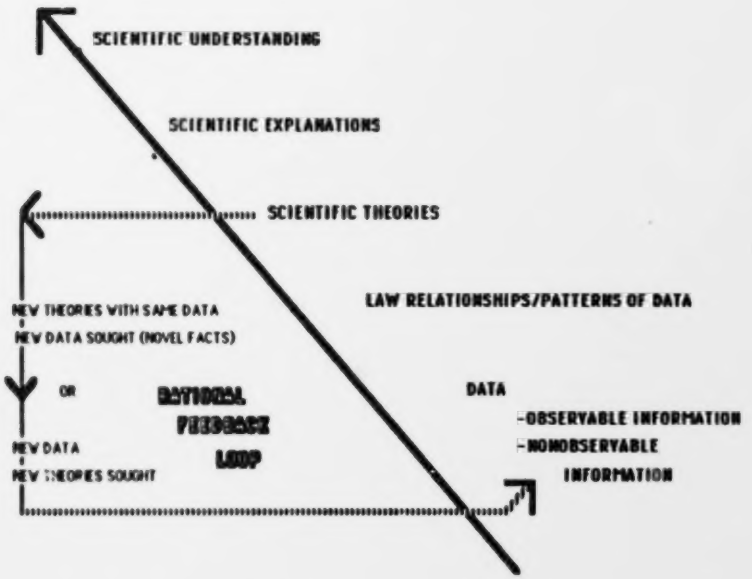

Figure 3 - Scientific theories are an important step in the generation of scientific understanding. Furthermore, changes in theory result in changes to all other steps.

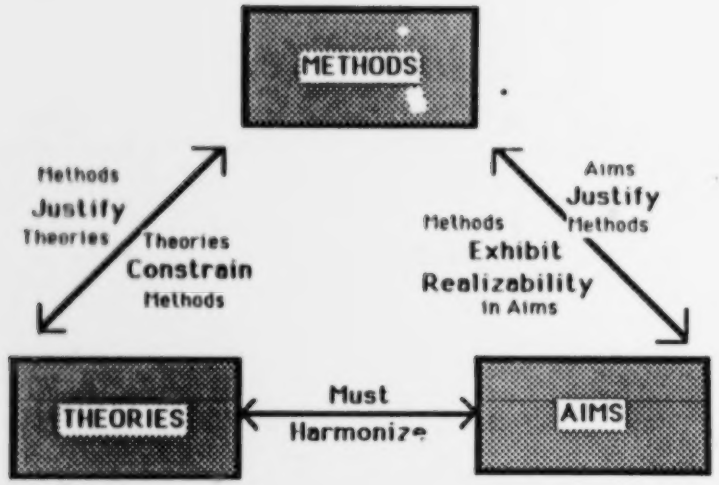

Figure 4. - The Triadic Newtork of Justification (From Laudan 1984, p 63).